Plasma microturbulence simulation of instabilities at highly disparate scales

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Drift waves and tokamak plasma turbulence

Role in the context of fusion research

- **Plasma performance**:

  In tokamak plasmas, performance is limited by turbulent radial transport of both energy and particles.

- **Gradient-driven**:

  This turbulent transport is caused by drift-wave instabilities, driven by free energy in plasma temperature and density gradients.

- **Unavoidable**:

  These instabilities will persist in a reactor.

- **Various types (asymptotic theory)**:

  ITG, TIM, TEM, ETG . . . $+$ Electromagnetic variants (AITG, etc).

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Electron-ion Scale Separation

Parameterized by the electron-to-ion mass ratio

- Turbulence extends from **electron** (ρ_e) scales to **ion** (ρ_i) scales:

$$\frac{(L_x)_i}{(L_x)_e} \sim \mu \qquad \frac{(L_y)_i}{(L_y)_e} \sim \mu$$

- Characteristic times are **short for electrons** and **long for ions**:

$$\frac{\tau_i}{\tau_e} \sim \frac{a/v_e}{a/v_i} \sim \mu$$

- Critical parameter is the **root of the mass-ratio**:

$$\mu \doteq \sqrt{\frac{m_i}{m_e}} \simeq 60$$

Coupled ITG/TEM-ETG Transport

Motivation and What's New

- Is energy transport from **electron-temperature-gradient** (ETG) modes significant?
  - Is it a large fraction of the total χ_e?
  - Could it account for **residual electron transport** in an ITB?
  - How do we define it, since its only part of χ_e?
- GYRO is well-suited (scalable, efficient) to study this problem.
- This work was supported by a DOE **INCITE** computer-time award.
- First simulations to resolve both electron-scale and ion-scale turbulence.

Let's define χ_e^{ETG} as that which arises from $k_\theta \rho_i > 1.0$

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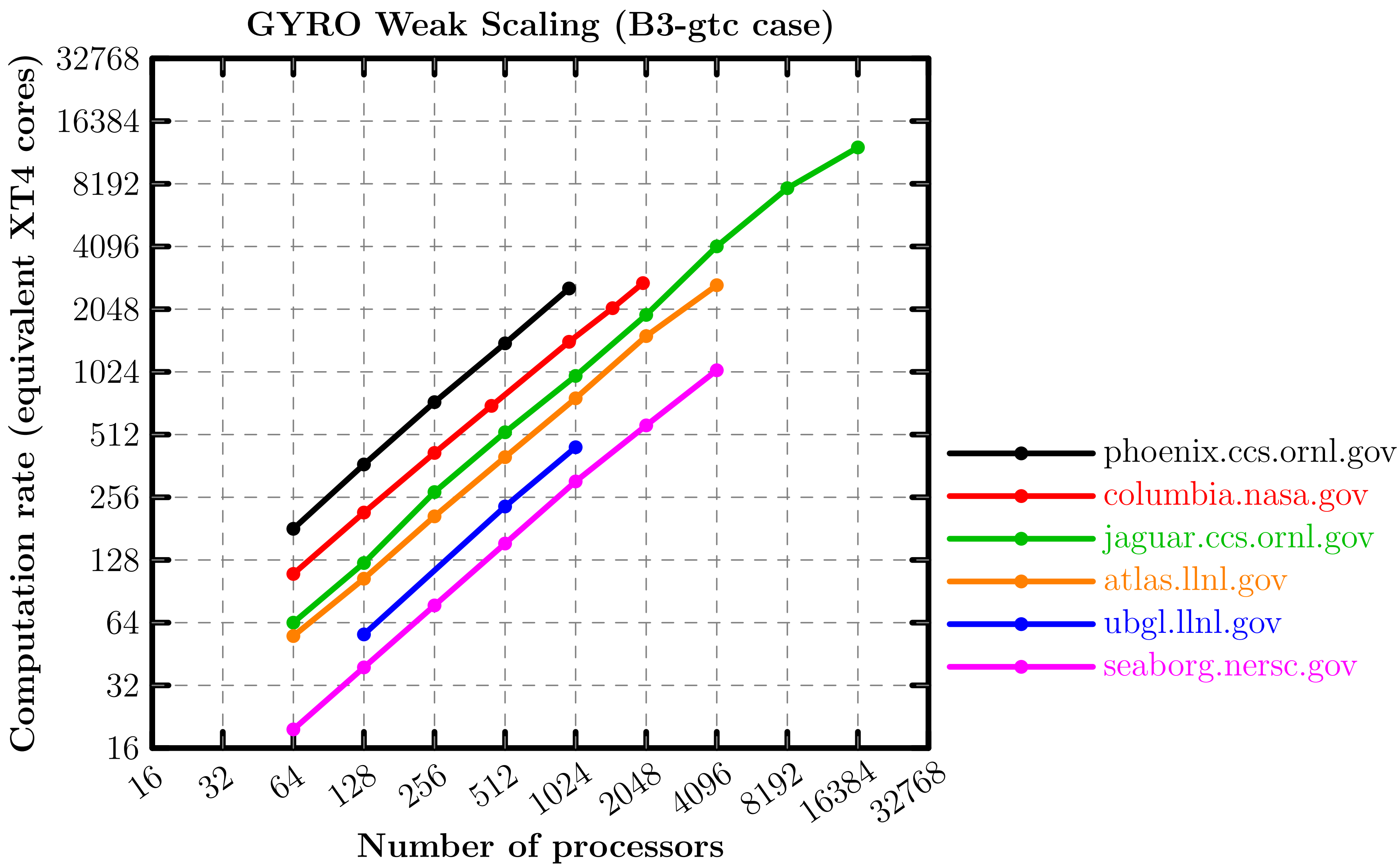
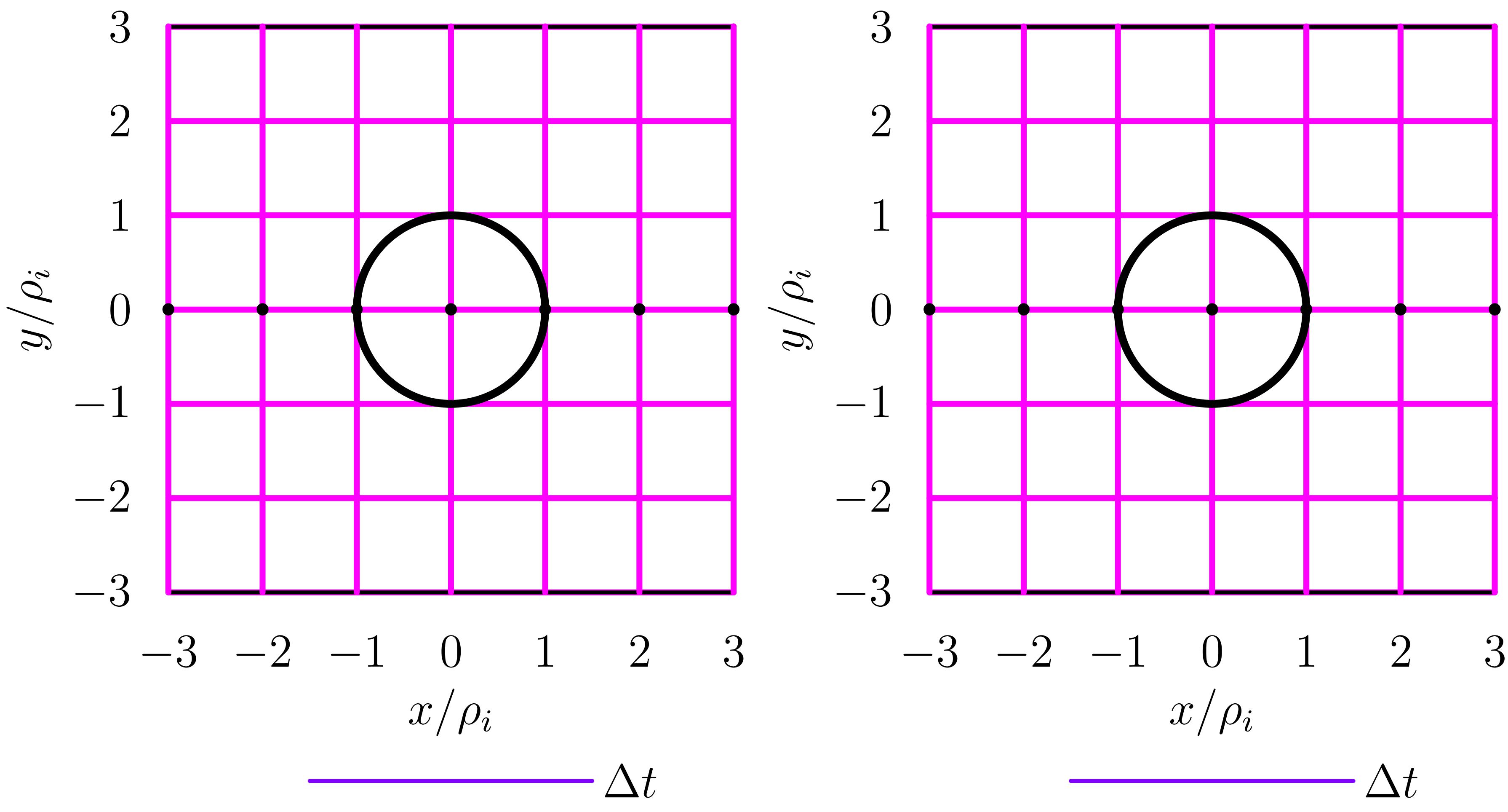
GYRO Weak Scaling

Increasing velocity-space resolution at fixed spatial grid



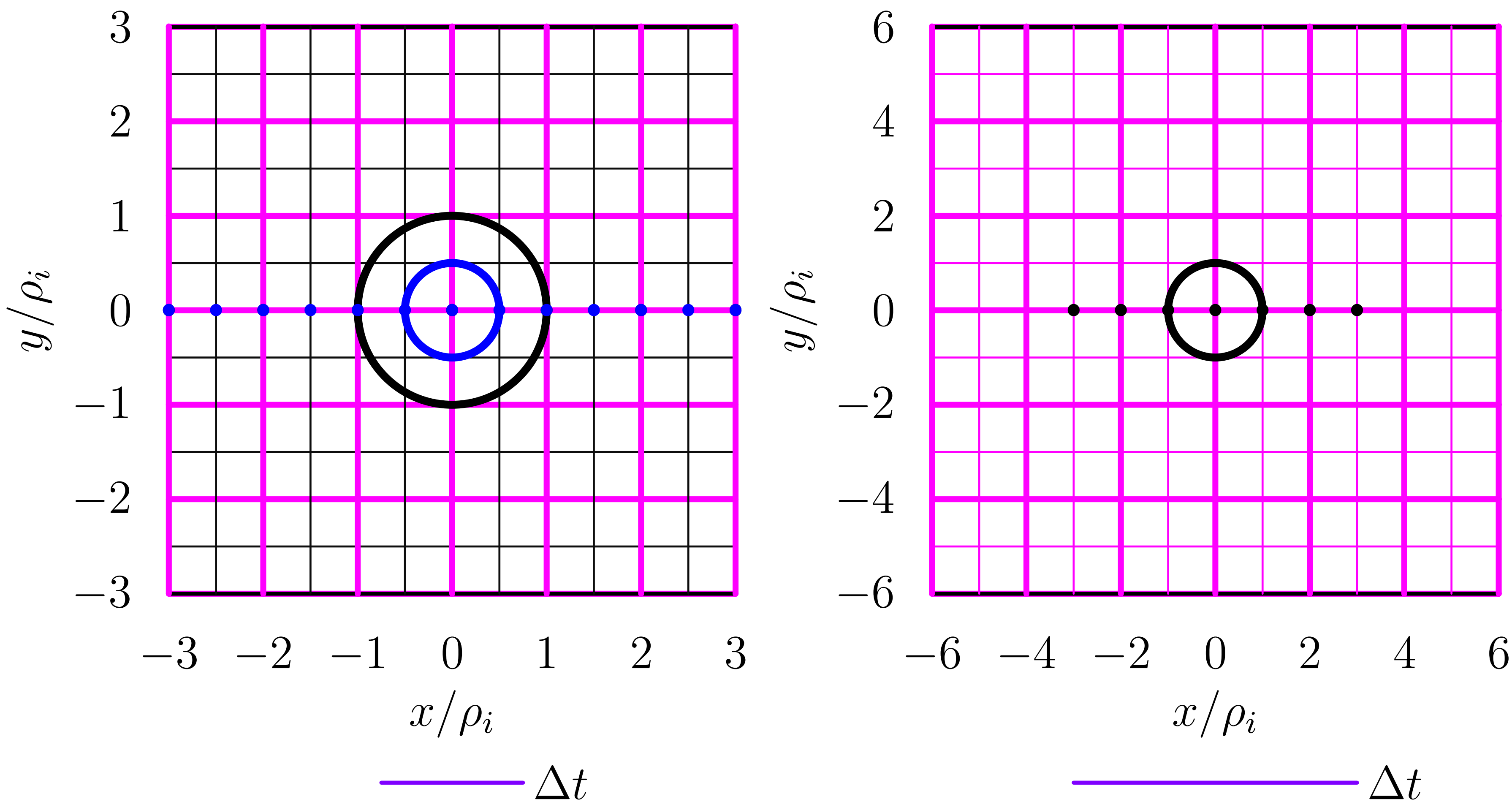
Multi-scale simulations require spatial grid refinement

$\mu = 1,\ k_\theta \rho_i \leq 1$



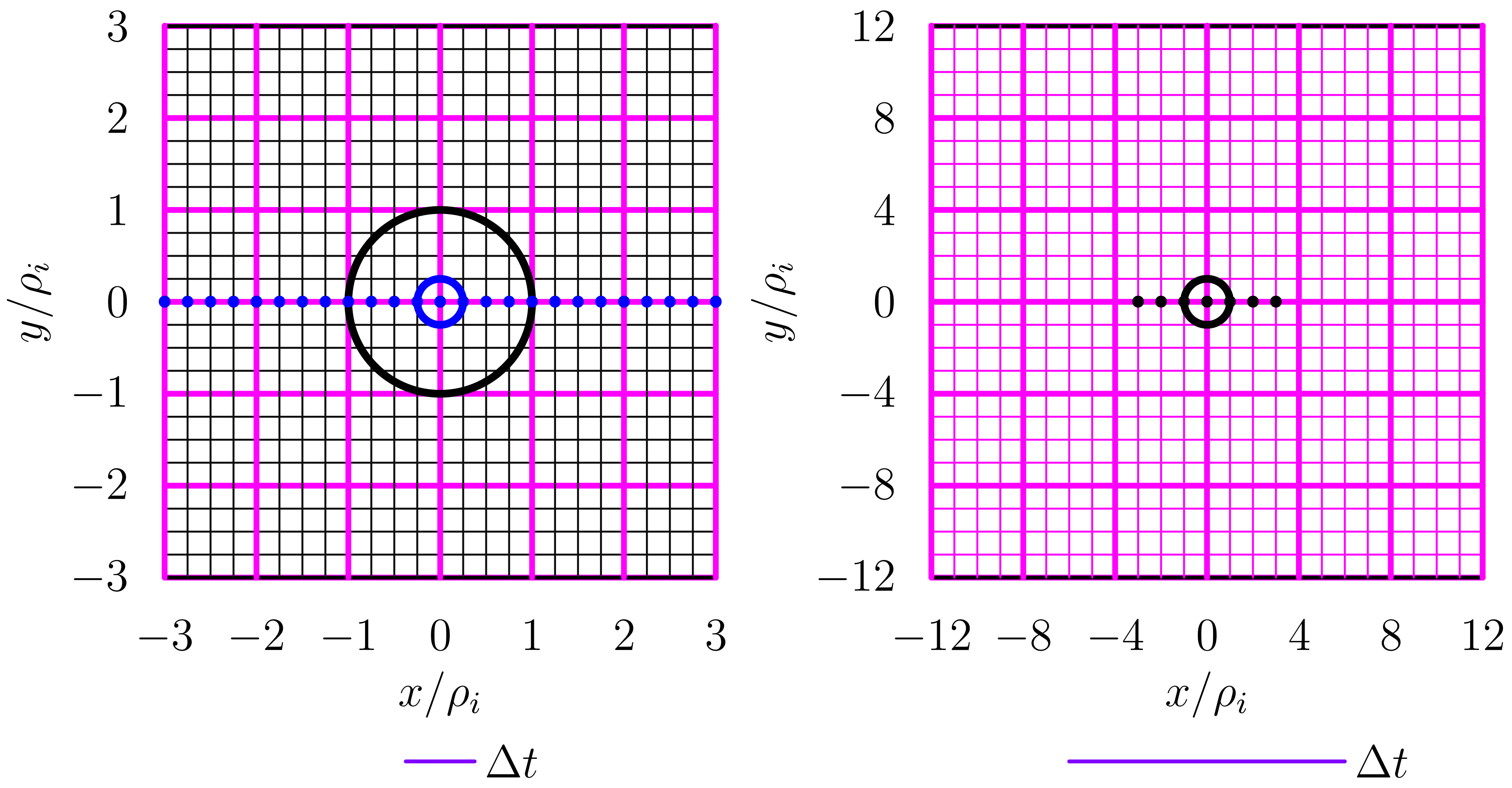
Multi-scale simulations require spatial grid refinement

$\mu = 2,\ k_\theta \rho_i \leq 2$



Multi-scale simulations require spatial grid refinement

$\mu = 4,\ k_\theta \rho_i \leq 4$



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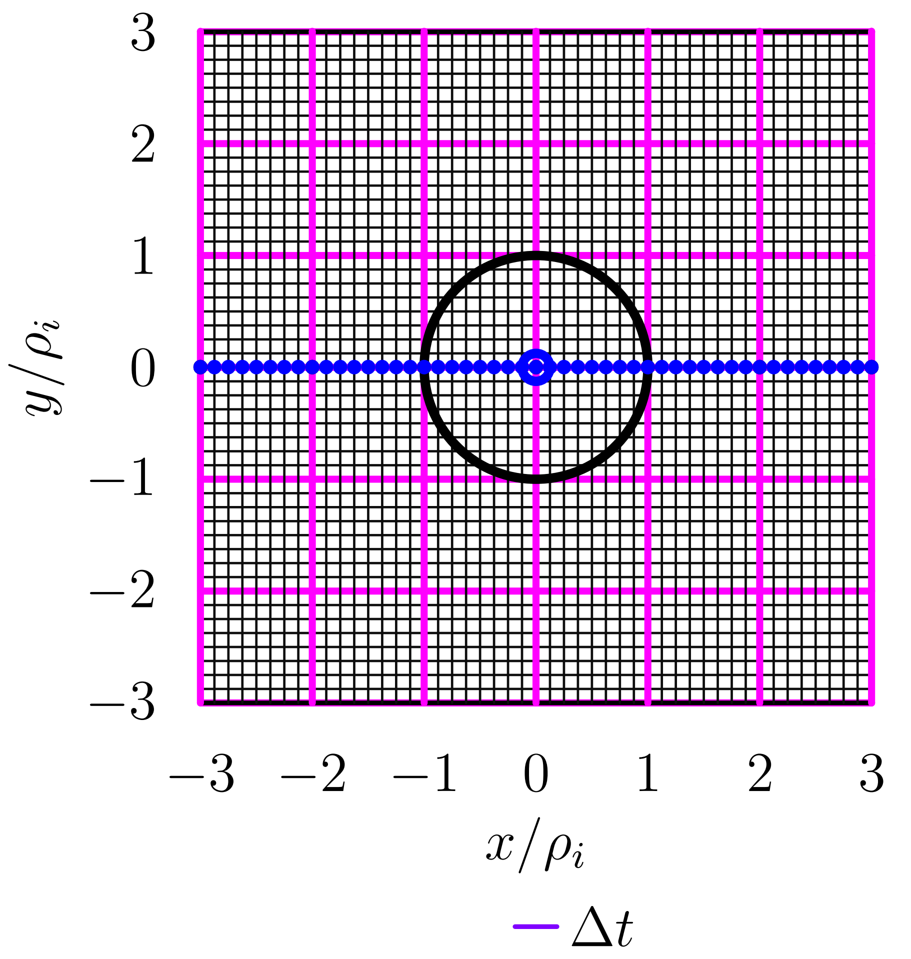
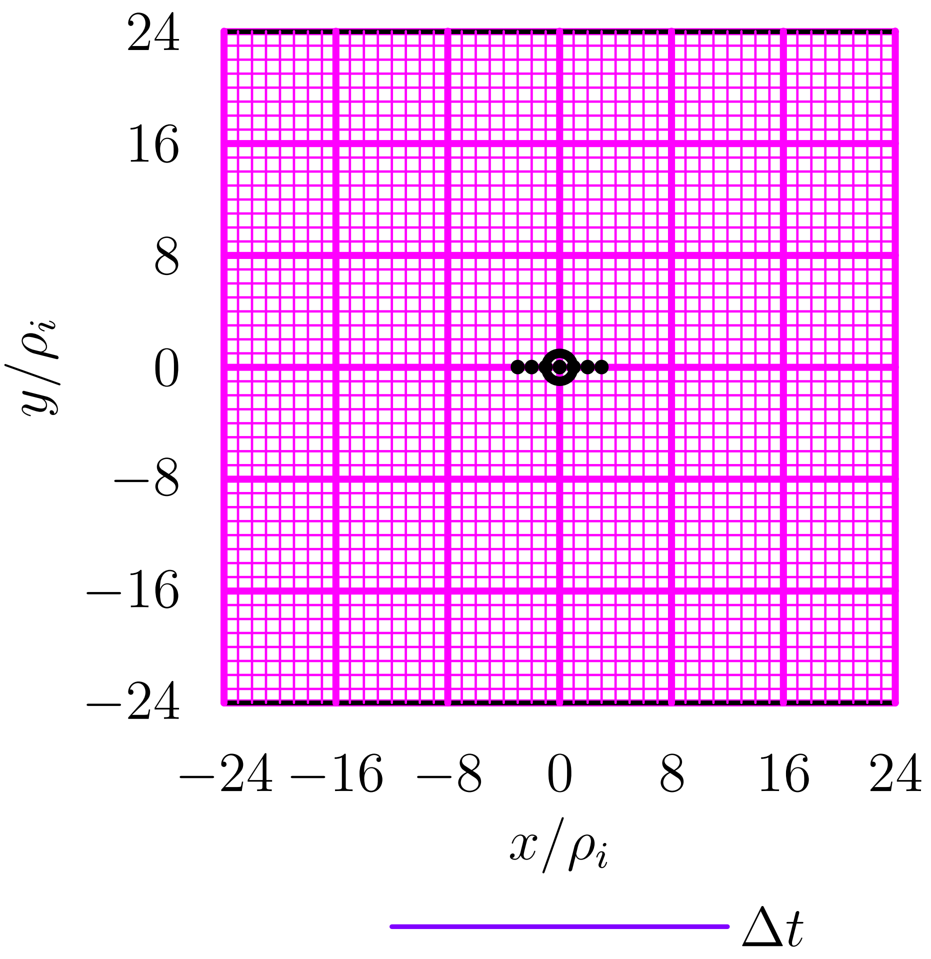
Multi-scale simulations require spatial grid refinement

$\mu = 8,\ k_\theta \rho_i \leq 8$





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Three Ways to Treat Ion Dynamics

Definitions

1. **ETG-ai** = **adiabatic ion model of ETG** **(CHEAP)**

   ion scales do not enter

2. **ETG-ki** = **kinetic ion model of ETG** **(EXPENSIVE)**

   (no ion drive) $\longrightarrow a/L_{Ti} = 0.1,\;\; a/L_{ni} = 0.1$

3. **ETG-ITG** = **kinetic ion model of ETG** **(EXPENSIVE)**

   (ion drive) $\longrightarrow a/L_{Ti} = a/L_{Te},\;\; a/L_{ni} = a/L_{ne}$

Other parameters taken to match the **Cyclone base case**:

$$q = 1.4,\; s = 0.8,\; R/a = 2.78,\; a/L_{Te} = 2.5,\; a/L_{ne} = 0.8$$

The ETG-ai Model

The minimal model of ETG, but is it sensible?

- Basis of **original studies** by Jenko and Dorland.
- Take **short-wavelength limit** of the ion response:

$$\delta f_i(\mathbf{x}, \mathbf{v}, t) \rightarrow -n_0 \, F_M(|\mathbf{v}|) \, \frac{e \, \delta\phi(\mathbf{x}, t)}{T_i} \quad .$$

- **Nearly isomorphic** to usual adiabatic-electron model of ITG.
- Computationally simple – ion time and space scales removed.
- The **physics of zonal flows** is dramatically altered.

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Three Ways to Treat Ion Dynamics

Comparison of linear growth rates

1. **ETG-ai**

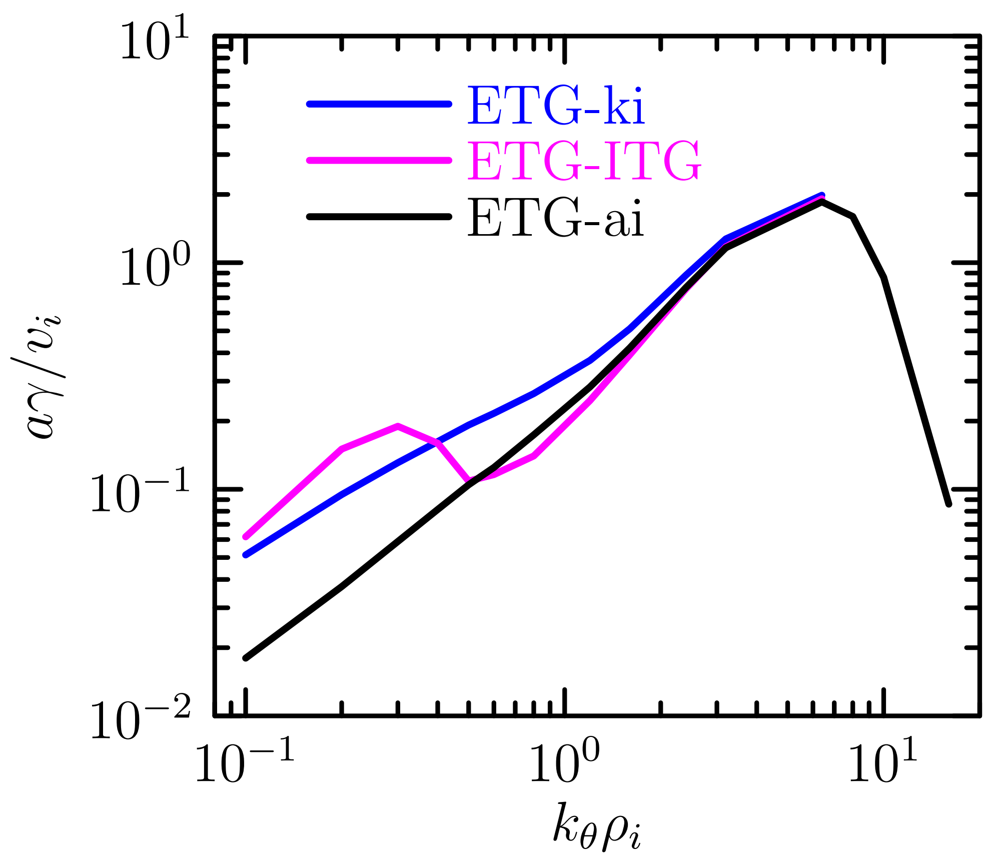
   adiabatic ion model of ETG

2. **ETG-ki**

   kinetic ion model of ETG

3. **ETG-ITG**

   kinetic ion model of ETG



$k_\theta = \dfrac{nq}{r}$ where n is the toroidal **eigenmode** number.

Reduced Mass Ratio for Computational Efficiency

A crucial method to cut corners (for ETG-ki and ETG-ITG models)

- Can deduce essential results using $\mu < 60$.
- Fully-coupled simulations, as shown, use **light kinetic ions**:

$$\mu \doteq \sqrt{\frac{m_i}{m_e}} = 20, 30 \quad .$$

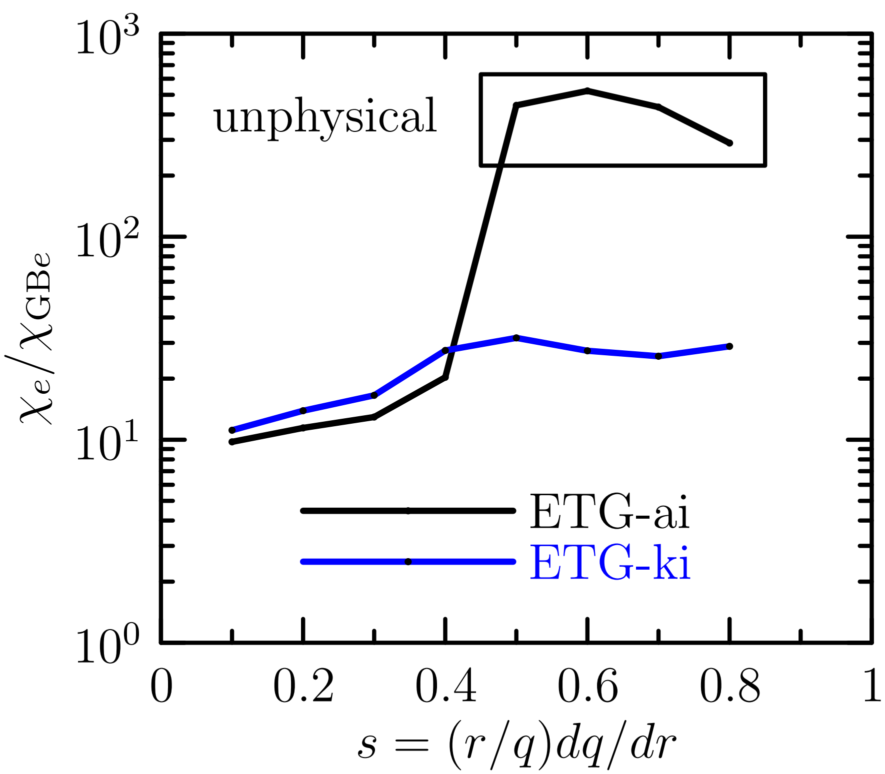
- Simulation cost scales roughly as $\mu^{3.5}$: $\left(\frac{30}{20}\right)^{3.5} \simeq 4$.

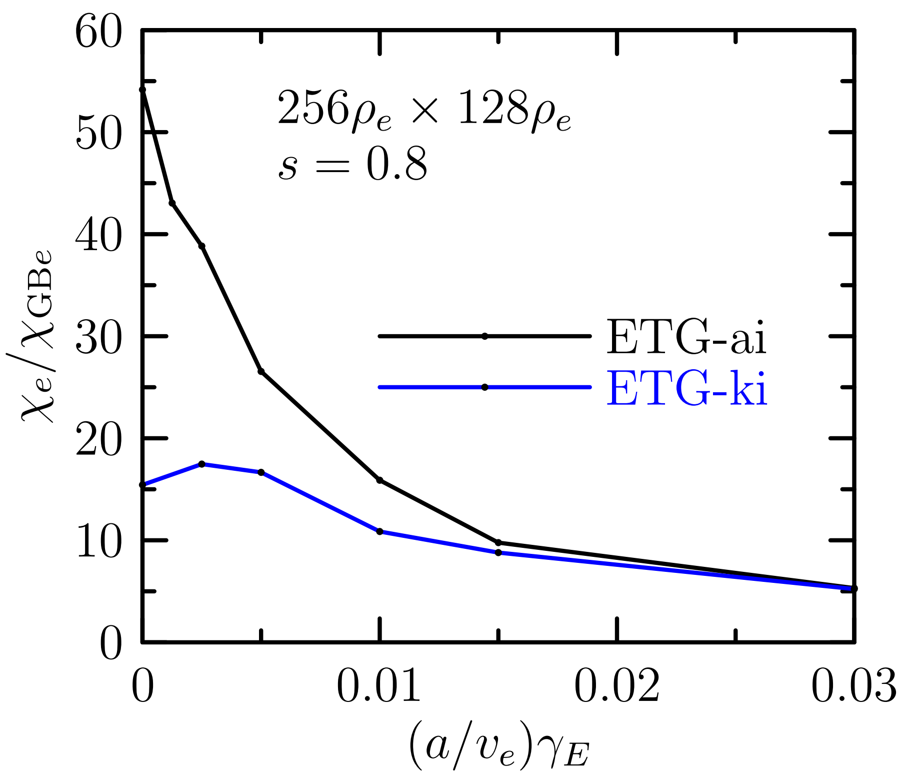
$\mu = 20$ **5 days on Cray X1E (192 MSPs)**

$\mu = 30$ **5 days on Cray X1E (720 MSPs)**

The failure of the ETG-ai model

Can illustrate the divergence by parameter variation





$E \times B$ shearing rate: γ_{E}

The ETG Cyclone Base Case **DOES NOT SATURATE PHYSICALLY**

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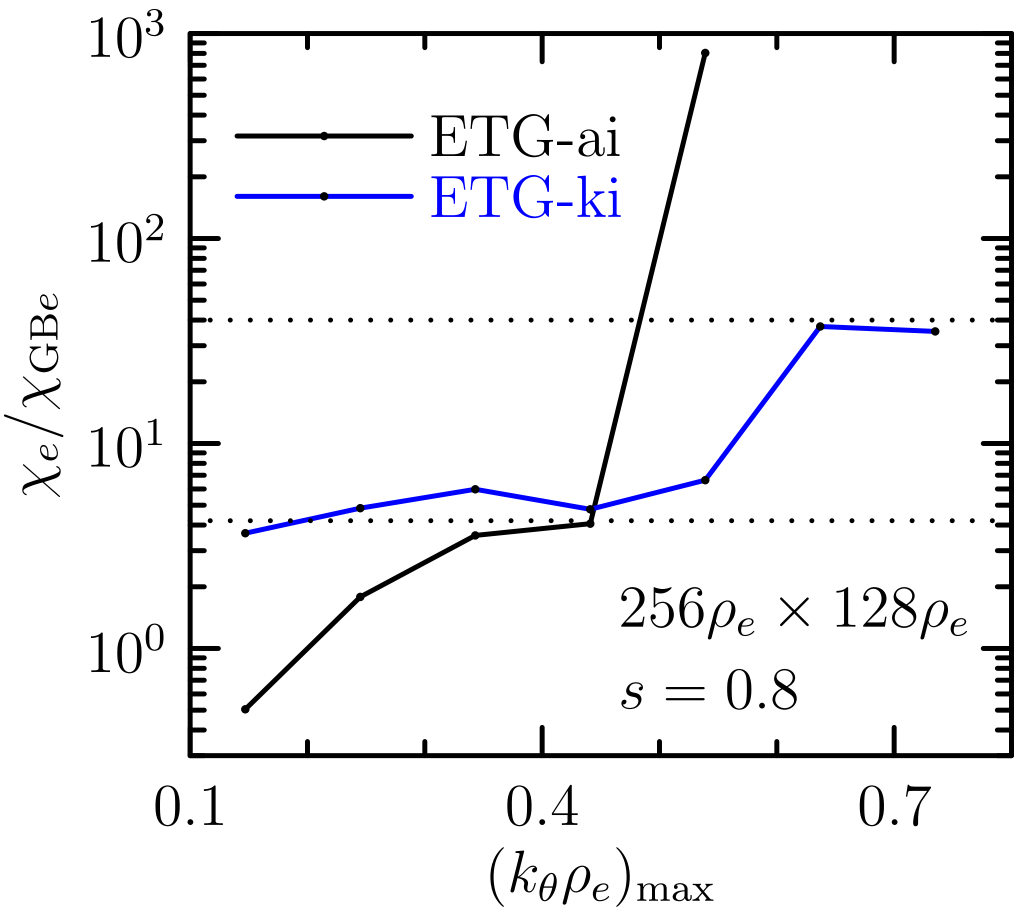
The failure of the ETG-ai model

A false asymptote occurs if short-wavelength modes are underresolved



Possible low-level saturation of PIC codes via **higk-k noise**

$$\gamma_{\mathrm{noise}} \propto -D_{\mathrm{noise}} k_\perp^2$$

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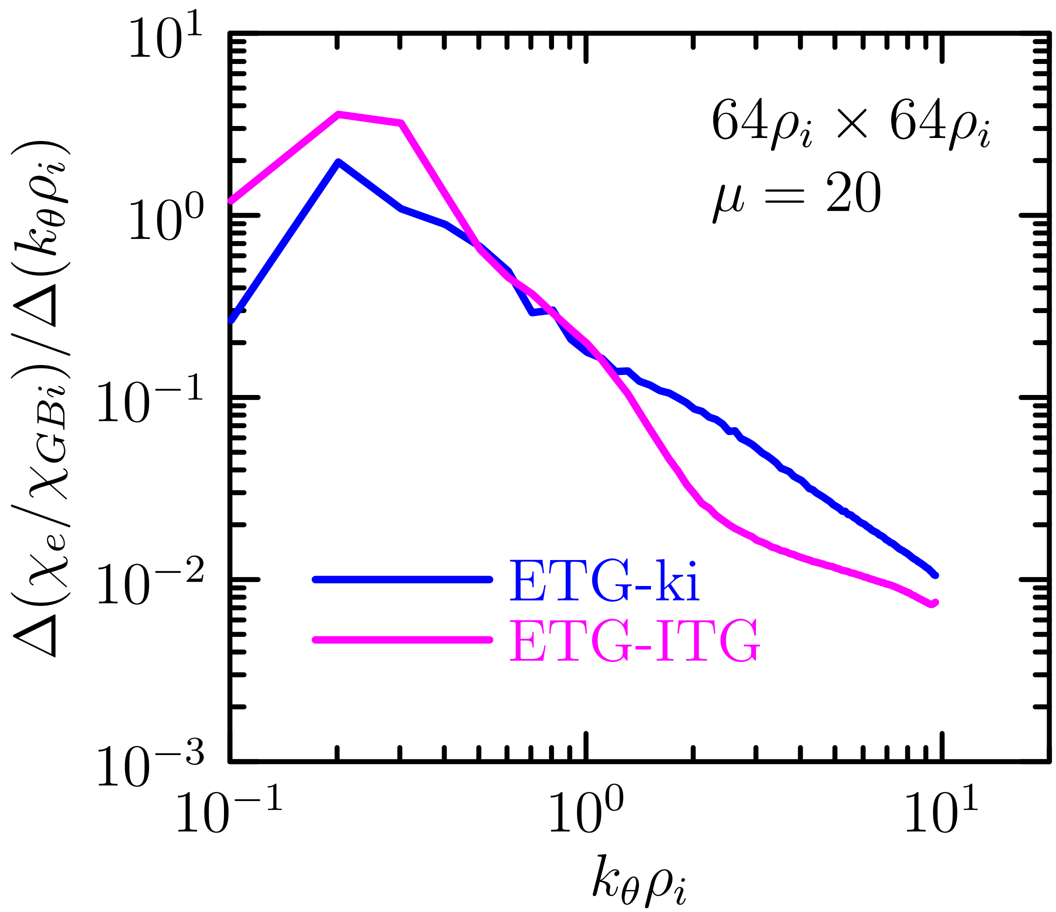
The Effect of Ion Gradients: ETG-ITG versus ETG-ki

Finite ion gradients reduce χ_e^{ETG}



The reduction in ETG-ITG short-wavelength transport is not fully understood; probably the result of **strong long-wavelength shearing**.

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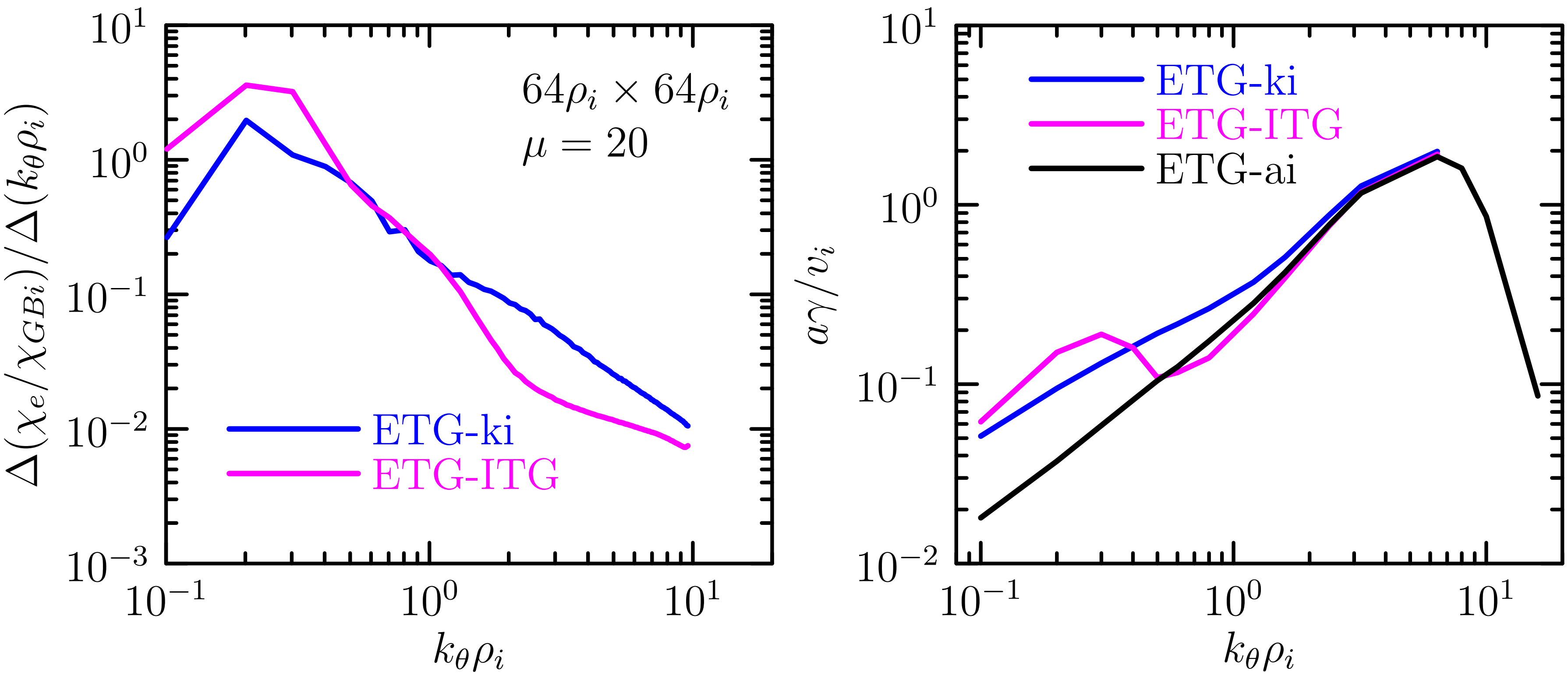
Understanding the Effect of Ion Gradients

What is the dominant physical mechanism for this reduction?



χ_e is the **nonlinear electron heat flux**.

$a\gamma/v_i$ is the **linear growth rate**.

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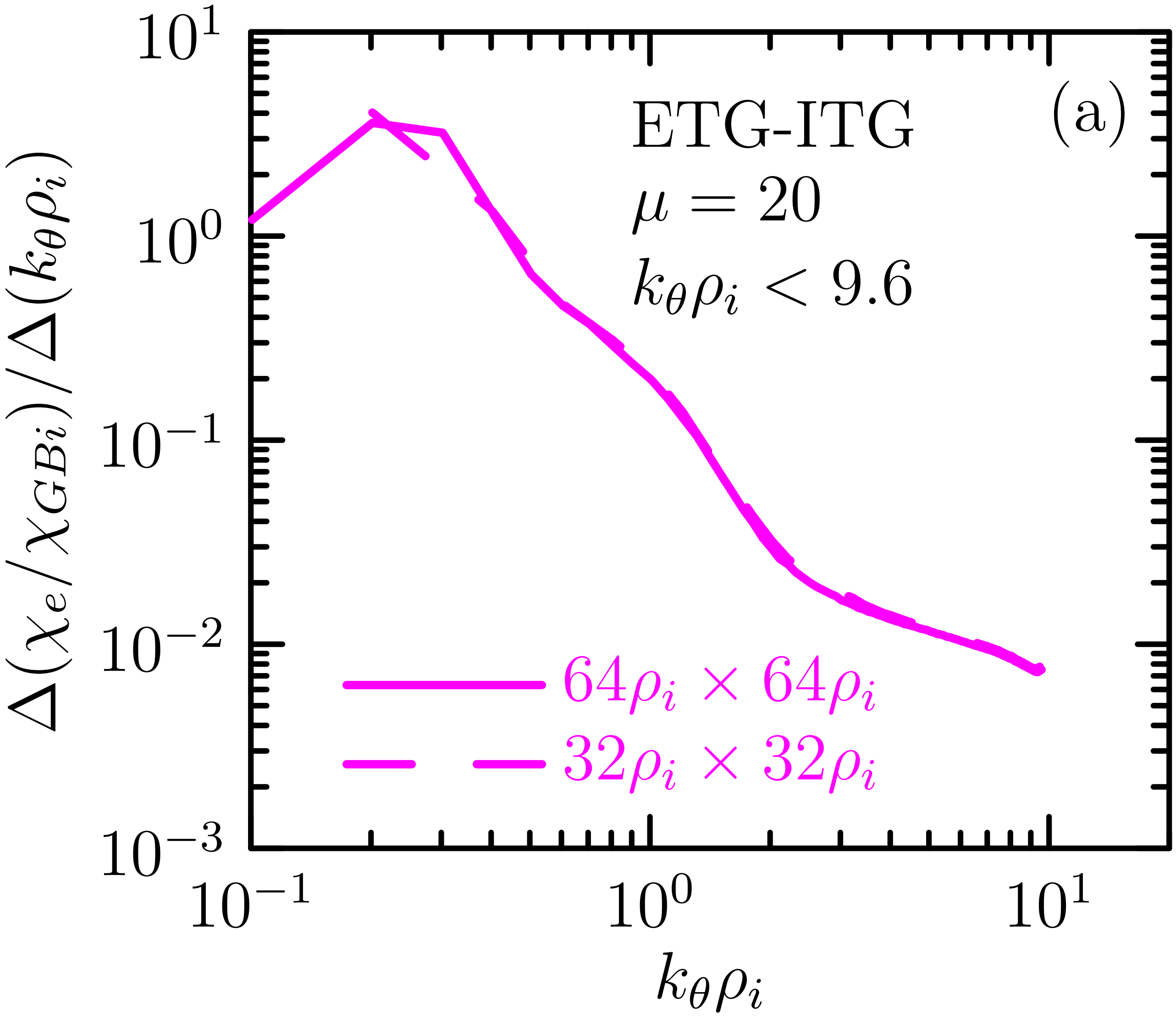
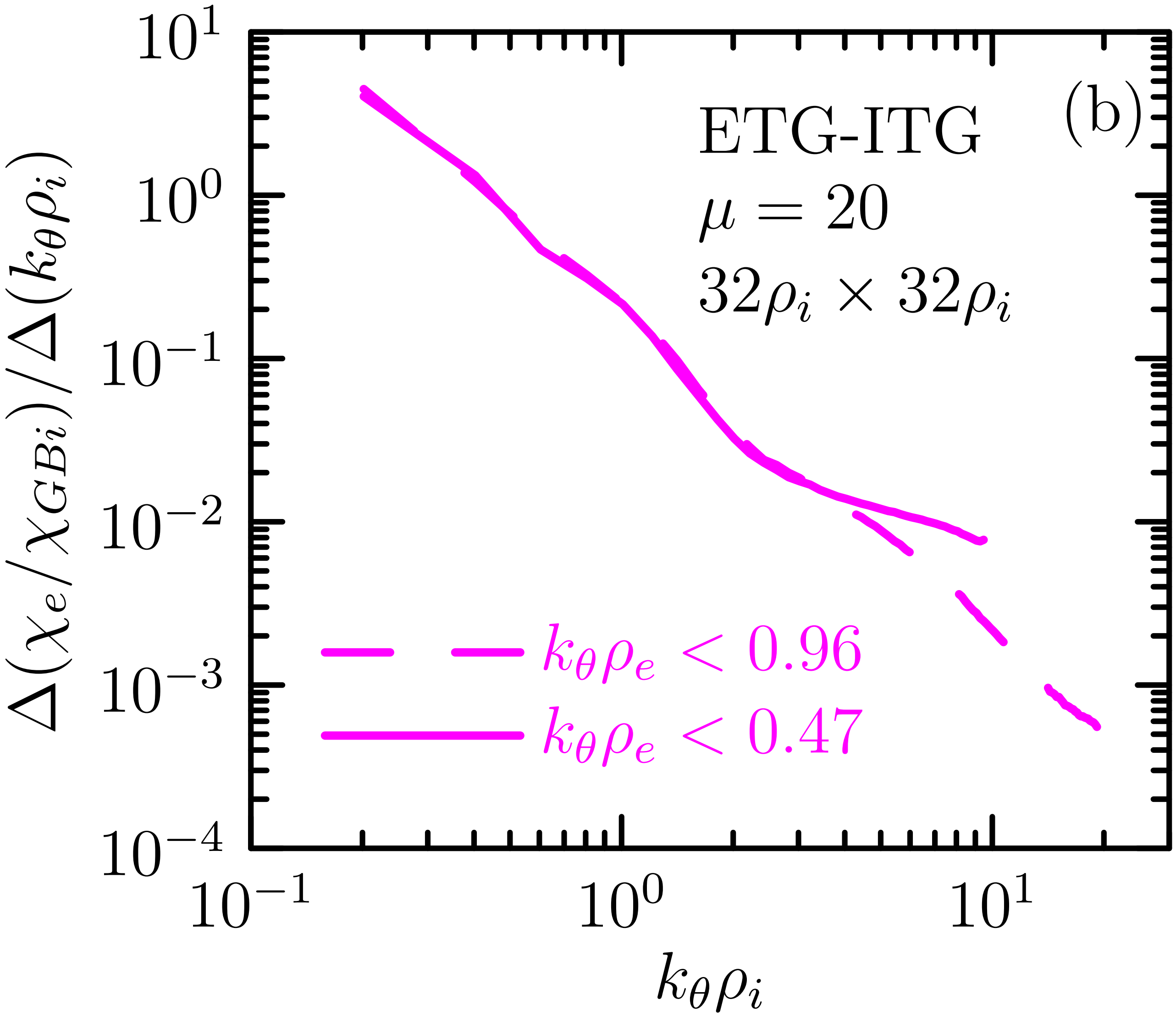
Effect of Reduced Perpendicular Box Size

A $32\rho_i \times 32\rho_i$ box is enough to capture the physics for $k_\theta \rho_e > 0.1$.



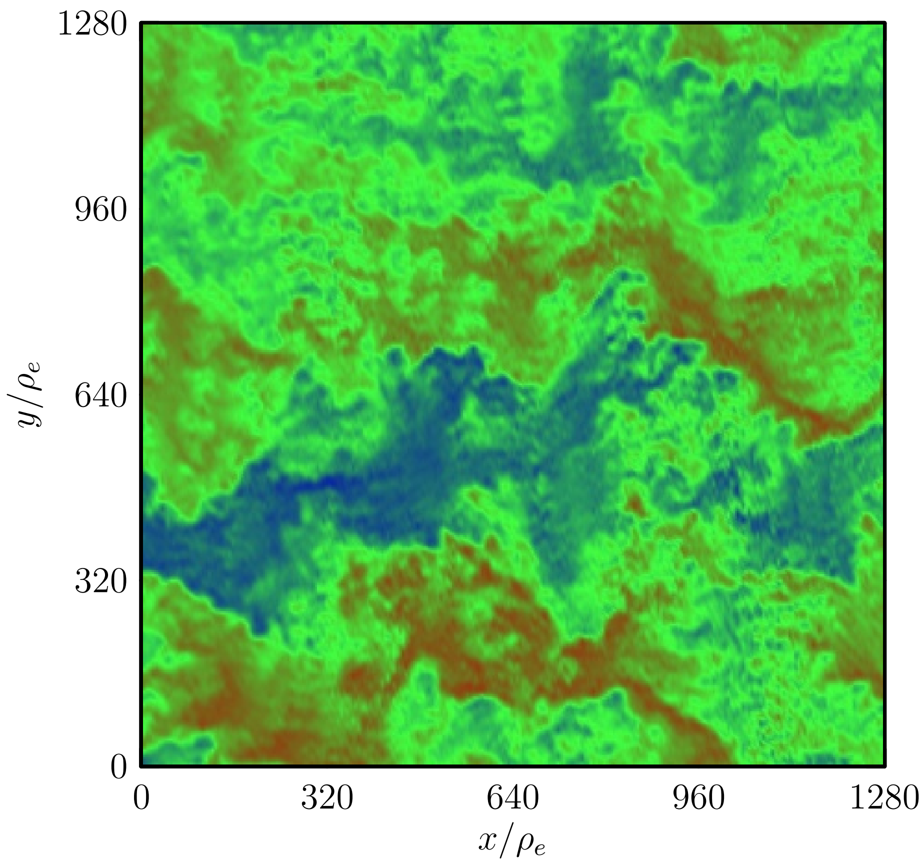
Effect of perpendicular grid refinement

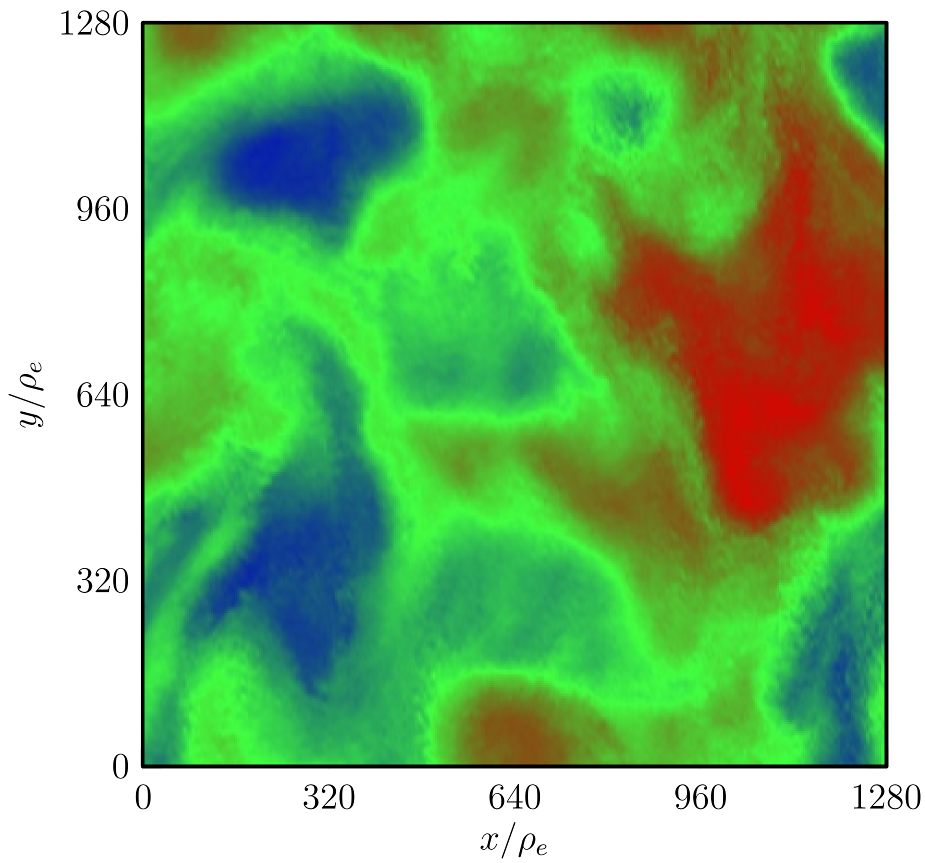
Remove spectral lip (4 days on 1536 XT3 CPUs, courtesy M. Fahey)



Perpendicular Spectral Intensity of Density Fluctations

ETG-ITG spectrum is highly isotropic (streamerless) for $k_\perp \rho_i > 0.5$

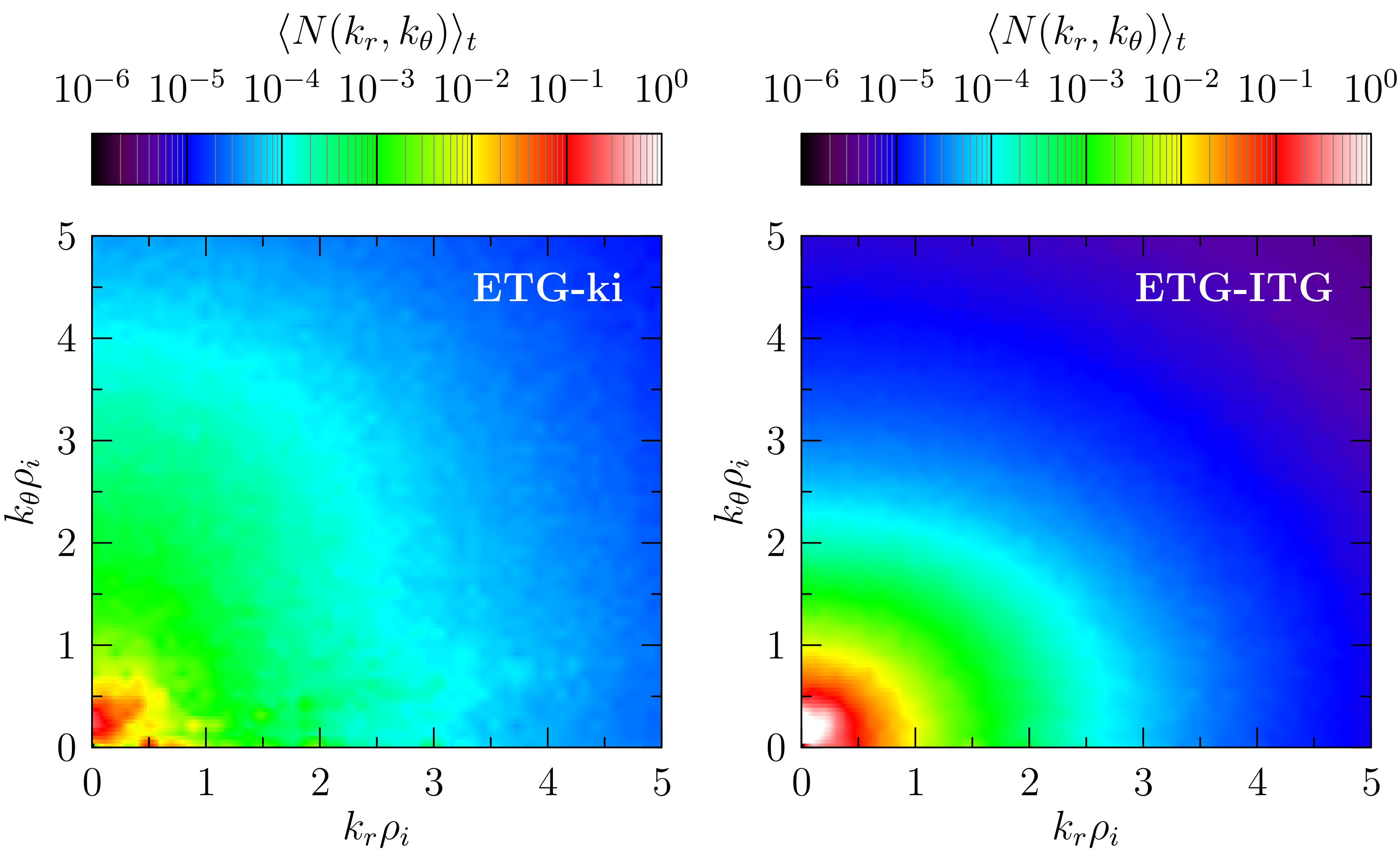




Electron-scale eddies apparent in ETG-ki (left) simulation.

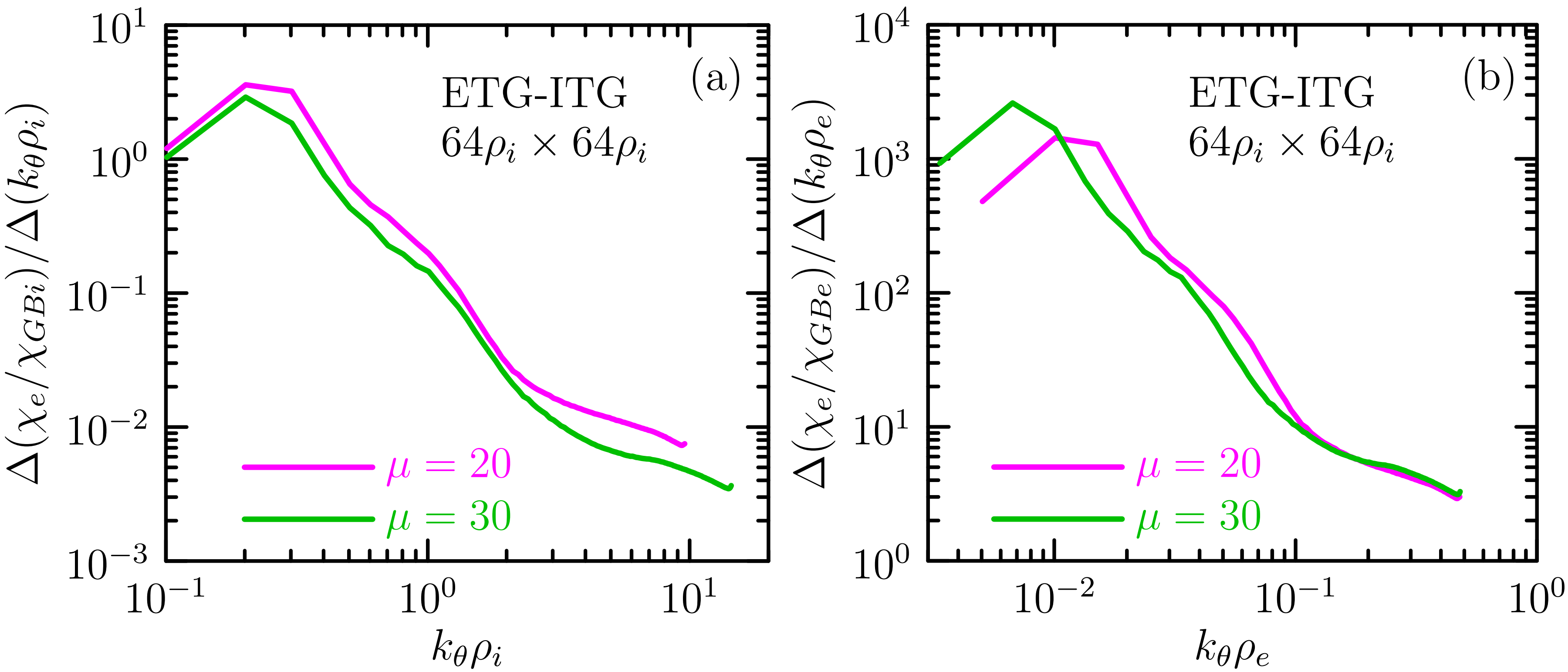
Perpendicular Spectral Intensity of Density Fluctations

ETG-ITG spectrum is highly isotropic (streamerless) for $k_\perp \rho_i > 0.5$



Mass-ratio Comparison in Electron Units

Curve approaches universal shape at short wavelength ($k_\theta \rho_e > 0.1$)



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Electron Transport Result Matrix

About 16% (8%) of electron transport comes from $k_\theta \rho_i > 1$ ($k_\theta \rho_i > 2$)

	μ	$k_\theta \rho_i < 1$	$k_\theta \rho_i > 1$	$k_\theta \rho_i > 2$	$k_\theta \rho_e > 0.1$
$\chi_i / \chi_{\mathrm{GB}i}$	20	7.378	0.054	0.011	
	30	7.754	0.043	0.009	
$\chi_e / \chi_{\mathrm{GB}i}$	20	2.278	0.367	0.183	
	30	**1.587**	**0.296**	0.157	
$D / \chi_{\mathrm{GB}i}$	20	-0.81	0.134	0.009	
	30	-1.60	0.074	0.010	
$\chi_e / \chi_{\mathrm{GB}e}$	20				**3.67**
	30				**3.76**

Coupled ITG/TEM-ETG Transport

Summary of main results

- The **adiabatic-ion** model of ETG is **poorly-behaved**.
  - Transport becomes **unbounded** for some parameters.
  - Using the **kinetic ion response** cures the problem.
- Ion-temperature-gradient (ITG) transport is **insensitive** to ETG.
- Increased ITG drive can **reduce** ETG transport.
  - Unclear how much of the effect is **linear** and how much is **nonlinear**.
- What fraction of χ_e is χ_e^{ETG}?
  - Only **10% to 20%** in the absence of $\mathbf{E}\times\mathbf{B}$ shear.
  - Up to **100%**, as ITG/TEM is quenched by $\mathbf{E}\times\mathbf{B}$ shear.

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